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Magnetic Energy Storage

Technical Field

This invention relates to a superconducting magnetic energy storage (SMES) device of the kind comprising a coil for connection in series with a voltage source, e.g. a dc voltage source, and wound from a superconducting cable having superconducting means which, in use, is maintained at cryogenic temperatures below its critical temperature (T_c) and which is surrounded by electrical insulation, and switch means for short-circuiting the coil. Although the invention primarily relates to high-temperature superconducting cables, the invention is also applicable to low-temperature superconducting cables because of the high magnetic field in magnetic energy storage.

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Background of the Invention

The concept of superconducting magnetic energy storage (SMES) is well known. The principle of SMES is that energy is stored as magnetic energy in a coil having an inductance L, the amount of energy stored being given by $\frac{1}{2}.L.I^2$, where I is the dc current.

The inductance L of a coil is given through the well-known relationship:

$$L = (\mu_0 \mu_r N^2 A) \div l$$

where $\mu_0 = 4\pi x 10^{-7}$ As/Vm, μ_r is the permeability of material in the magnetic circuit of a solenoid (which is 1 for air and around 10000 or higher for oriented laminated quality steel, provided the magnetic flux density B is sufficiently low), N is the number of windings, A is the cross-sectional area and l the length of the coil.

Since the magnetic energy E to be stored in a SMES device is $E = \frac{1}{2}.L.I^2$, it is evident that both current and inductance should be maximised. The maximum current is

given through the properties of a superconductor at given temperature, magnetic field and current density.

The inductance could be maximised by utilising a magnetic material in the magnetic circuit having a high permeability. Unfortunately, there are no known materials having a high permeability at high flux densities. In fact at B around 2 Tesla, even the best materials go into saturation and, in addition, core losses (hysteresis and eddy) increase drastically in the saturation region. If the magnetic moments of a material are perfectly aligned, it is theoretically possible to reach a maximum flux density of 2.12 Tesla for iron. Due to the high currents of superconductors, the flux densities are also high, in fact densities of 5 T and more are not uncommon. Thus magnetic material should not be included in the magnetic circuit, at least not in regions of high B. In general, μ_r is then equal to one.

The inductance can also be increased by choosing a high number of windings N. If a solenoid is wound, then the winding density, that is the number of windings per unit length, is determined by the cross-sectional area of the conductor and its insulation.

The ratio of cross-sectional area to length is also an important parameter for the inductance. The aim should be to achieve a large cross-section and a short coil length. Thus pancake or disk windings are often designed as a preferred coil for achieving high inductances.

SMES devices have a high efficiency and high energy density compared with competing systems for storing energy. SMES devices can have a rapid response to demands of storing or discharging. In addition SMES devices can be used not only for load-levelling but also for load-following, for spinning reverse, for transient stabilization and for synchronous resonance damping. SMES can provide not only

energy savings but also a larger freedom of power system operation.

Normally SMES devices are built for storing energy up to about 1 MW, but there is a demand for SMES devices with higher energy storage capability. Current solutions for larger SMES devices involve oversizing of equipment and the usage of multiple feeders connected to different transmission systems.

Conventional SMES devices operate with high current source at low voltage. When used in an ac power system an ac-dc converter can be used for converting the power to and from the SMES device. Operation of SMES devices connected to power networks will include a transformer.

A SMES device is normally built as a coil. In order to maximize the storage capability, the inductance should be as high as possible. Therefore, the superconductor is wound into a pancake, for example a 4 T background coil for SMES as described in "Design and construction of the 4 T background coil for the navy SMES cable test apparatus", IEEE Transactions on Applied Superconductivity, Vol 7, No 2, June 1997. The SMES devices are normally connected to voltages of up to about 500 V and currents of around 1000 A.

A large SMES device for 30MW is described in IEEE Transactions on Applied Superconductivity, Vol 7, No. 2, June 1997 in the article "Quench Protection and Stagnant Normal Zones in a Large Cryostable SMES" and involves a coil assembled from a multiple double pancake structure. The application of this SMES device requires a high power discharge and the operating voltage is desired to be up to 3.4 kV.

Another method of storing magnetic energy can be by winding the conductor directly as a solenoid. An example of a test coil is described in "Design, manufacturing and cold test of superconducting coil and its cryostat for SMES

applications", IEEE Transactions on Applied Superconductivity, Vol 7, No. 2, June 1997, where a solenoid consists of a NbTi conductor with 4500 turns, 30 layers and an inner winding radius of 120 mm.

Summary of Invention

An aim of the present invention is to have a high voltage system comprising an SMES device, where superconducting conductors of the SMES device are insulated against high voltage and the insulation is concentric around the conductors.

According to one aspect of the present invention there is provided a SMES device of the kind referred to, characterised in that the said electrical insulation comprises an inner layer of semiconducting material electrically connected to said superconducting means, an outer layer of semiconducting material at a controlled electric potential, e.g. earth potential, along its length and an intermediate layer of solid electrically insulating material positioned between said inner and outer layers.

In this specification the term "semiconducting material" means a material which has a considerably lower conductivity than an electrical conductor but which does not have such a low conductivity that it is an electrical insulator. Suitably, but not exclusively, a "semiconducting material" should have a volume resistivity of from $1\text{-}10^5\ \Omega\cdot\text{cm}$, preferably from $1\text{-}10^3\ \Omega\cdot\text{cm}$, more preferably 10-500 $\Omega\cdot$cm and most preferably 10-100 $\Omega\cdot$cm, typically 20 $\Omega\cdot$cm.

The present invention is not limited to high temperature superconductivity. Due to the high magnetic field in magnetic energy storage, low temperature superconductors are still attractive, even though they require cryostats operating between 1-15 K, depending on the type of low temperature superconductor utilised. Well known examples are based on Niobium, such as NbTi, Nb_3Sn and Nb_3Al.

Other examples are V_3Ga and Nb_3Ge. The most common superconductor used is NbTi which can be utilised in magnetic field densities up to approximately 9 T at 4.2 K (or 11 T at 1.8 K). For higher field densities, NbTi cannot be used and is replaced by Nb_3Sn

An SMES device according to the invention is made from cable-like conductors which can be manufactured according to conventional principles of cable manufacturing. The insulation is such that it can withstand high voltages in the range of 1 kV and upwards to the voltages used for high voltage dc current transmission.

The invention allows a high voltage system comprising an SMES device. The SMES device can be coupled to a high voltage network. This means that load-following can be effected on a transmission or distribution network and not only for a specific use on lower voltage as is the case with the SMES devices of today. This opens up possibilities to use SMES for storing energy to smooth load variations in a high voltage network on, for example, day-night basis or east-west basis. Also, an SMES device on high voltage can be capable of injecting large amounts of energy into a system under a short time, that is injecting a large amount of real power, which will allow for good control of the system.

The present invention allows a high voltage system comprising an SMES system which can be directly coupled to a high voltage of up to 800 kV and even above without the need to transform the voltage down. This can be achieved by insulating the superconducting means with an insulation system that can withstand high voltages. Such insulation systems are known for example from high voltage dc transmission systems.

A specific advantage of the present invention is that, since the SMES device operates at high voltage, the current can be reduced for a given power density. Thus, by

way of example only, for a conventional SMES device operating at 20 kV, a similarly powered SMES device according to the invention can operate at about 150 kV resulting in a reduction of the current of about 7.5 times. Since the magnetic force in the cable is proportional to current x magnetic flux density (B), the magnetic force is effectively reduced about 7.5 times. Furthermore, the amount of semiconductor saved will, in this example, amount to approximately 7.5 times. Similarly, the cooling losses will be essentially reduced. All these factors improve the economic attractiveness of the SMES device.

A further advantage with an SMES device operating at high voltages is that charging and discharging can be rapid. It is normally very time-consuming to charge, at least larger SMES devices, and by being able to connect the SMES device to a high voltage the charging time can be substantially reduced. Also the power that can be delivered from the SMES device is increased by increasing the voltage over the SMES device.

Another advantage is that an SMES device can be installed close to a large power generating unit, such as a nuclear power station. At a rapid close-down of a nuclear power station, there are great strains on the network. These can be effectively smoothed by a high voltage SMES device that is able to inject the corresponding power into the system and then allow for a slow ramp down of the power.

Another advantage of a high voltage SMES device is that there is no need for a transformer to be provided for transforming power to and from the SMES device. The SMES device can be directly coupled to a transmission or distribution network without intermediate step-up transformers. The elimination of transformers in the system leads to higher efficiency of the system. The performance of the SMES system will be greatly improved by being able to connect the SMES device directly to a power network and by

the increased efficiency that is created by the reduction of the number of components in the system.

Another advantage is that the SMES device is wholly electrically insulated in such a way that there is no electric field outside the superconducting cable. This facilitates the design of the mechanical structure holding the cables. It is possible to scale up the SMES device with less problems with the mechanical stability of the SMES device.

Another advantage of an SMES device with high voltage insulation is that discharges that normally occur in the electric system are prevented by the insulation system and the risk for bubble formation in the cooling medium is therefore reduced.

By connecting the coil directly to a high voltage dc source, e.g. to a high voltage ac-dc converter, charging and discharging of the coil is simplified. In particular, in an ac power transmission system, the need to transform the ac voltage down prior to connection to an ac-dc converter is eliminated. By holding the semiconducting outer layer at a controlled electric potential, e.g. ground or earth potential along its length, e.g. at spaced apart intervals along its length, the electric field generated by the superconducting means is contained within the electrical insulation.

Conveniently the coil and switch means are enclosed within a cryostat for maintaining the temperature of the superconducting means below its critical temperature (T_c). Alternatively, or in addition, the superconducting means may be internally cooled by a cryogenic fluid, e.g. liquid nitrogen, and externally thermally insulated. For example thermal insulation may conveniently be provided between the superconducting means and the surrounding electrical insulation. In some cases the electrical insulation can also function as thermal insulation.

By using for the intermediate layer only materials which can be manufactured with few, if any, defects and by providing the intermediate layer with the spaced apart inner and outer layers of semiconducting material having similar thermal properties, thermal and electric loads within the insulation are reduced. In particular the insulating intermediate layer and the semiconducting inner and outer layers should have at least substantially the same coefficients of thermal expansion (α) so that defects caused by different thermal expansions when the layers are subjected to heating or cooling will not arise. Ideally the electrical insulation is of substantially unitary construction. The layers of the insulation may be in close mechanical contact but are preferably joined or united together. Preferably, for example, the radially adjacent layers will be extruded together around the superconducting means. The superconducting cable is flexible at normal ambient temperatures and thus can be bent or flexed into its desired winding shape prior to operation at cryogenic temperatures.

Conveniently the electrically insulating intermediate layer comprises solid thermoplastics material, such as low or high density polyethylene (LDPE or HDPE)), polypropylene (PP), polybutylene (PB), polymethylpentene (PMP), ethylene (ethyl) acrylate copolymer, cross-linked materials, such as cross-linked polyethylene (XLPE), or rubber insulation, such as ethylene propylene rubber (EPR) or silicone rubber. The semiconducting inner and outer layers may comprise similar material to the intermediate layer but with conducting particles, such as carbon black, soot or metallic particles, embedded therein. Generally it has been found that a particular insulating material, such as EPR, has similar mechanical properties when containing no, or some, carbon particles.

The screens of semiconducting inner and outer layers form substantially equipotential surfaces on the inside and outside of the insulating intermediate layer so that the

electric field, in the case of concentric semiconducting and insulating layers, is substantially radial and confined within the intermediate layer. In particular, the semiconducting inner layer is arranged to be in electrical contact with, and to be at the same potential as, the superconducting means which it surrounds. The semiconducting outer layer is designed to act as a screen to prevent losses caused by induced voltages. Induced voltages could be reduced by increasing the resistance of the outer layer. Since the thickness of the semiconducting layer cannot be reduced below a certain minimum thickness, the resistance can only be reduced by selecting a material for the layer having a higher resistivity. However, if the resistivity of the semiconducting outer layer is too great the voltage potential between adjacent spaced apart points at a controlled, e.g. earth, potential will become sufficiently high as to risk the occurrence of corona discharge with consequent erosion of the insulating and semiconducting layers. The semiconducting outer layer is therefore a compromise between a conductor having low resistance and high induced voltage losses but which is easily connected to a controlled electric potential, typically earth or ground potential, and an insulator which has high resistance with low induced voltage losses but which needs to be connected to the controlled electric potential along its length. Thus the resistivity ρ_s of the semiconducting outer layer should be within the range $\rho_{min}<\rho_s<\rho_{max}$, where ρ_{min} is determined by permissible power loss caused by eddy current losses and resistive losses caused by voltages induced by magnetic flux and ρ_{max} is determined by the requirement for no corona or glow discharge.

If the semiconducting outer layer is earthed, or connected to some other controlled electric potential, at spaced apart intervals along its length, there is no need for an outer metal shield and protective sheath to surround the semiconducting outer layer. The diameter of the cable is thus reduced allowing more turns to be provided for a given size of winding.

The electrical insulation can be extruded over the superconducting means or a lapped concept can be used. This can include both the semiconducting layers and the electrically insulating layer. An insulation can be made of an all-synthetic film with inner and outer semiconducting layers made of polymeric thin film of, for example, PP, PET, LDPE or HDPE with embedded conducting particles, such as carbon black or metallic particles.

For the lapped concept a sufficiently thin film will have butt gaps smaller than the so-called Paschen minima, thus rendering liquid impregnation unnecessary. A dry, wound multilayer thin film insulation has also good thermal properties and can be combined with a superconducting pipe as an electric conductor and have coolant, such as liquid nitrogen, pumped through the pipe.

Another example of electrical insulation is similar to a conventional cellulose based cable, where a thin cellulose based or synthetic paper or non-woven material is lap wound around a conductor. In this case the semi-conducting layers can be made of cellulose paper or non-woven material made from fibres of insulating material and with conducting particles embedded. The insulating layer can be made from the same base material or another material can be used.

Another example is obtained by combining film and fibrous insulating material, either as a laminate or as co-lapped. An example of this insulation system is the commercially available so-called paper polypropylene laminate, PPLP, but several other combinations of film and fibrous parts are possible. In these systems various impregnations such as mineral oil or liquid nitrogen can be used.

The superconducting means may comprise low temperature semiconductors, but most preferably comprises high-temperature superconducting (HTS) materials, for

example HTS wires or tape helically wound on an inner tube. The HTS tape conveniently comprises silver-sheathed BSCCO-2212 or BSCCO-2223 (where the numerals indicate the number of atoms of each element in the $[Bi, Pb]_2\ Sr_2\ Ca_2\ Cu_3\ O_x$ molecule) and hereinafter such HTS tapes will be referred to as "BSCCO tape(s)". BSCCO tapes are made by encasing fine filaments of the oxide superconductor in a silver or silver oxide matrix by a powder-in-tube (PIT) draw, roll, sinter and roll process. Alternatively the tapes may be formed by a surface coating process. In either case the oxide is melted and resolidified as a final process step. Other HTS tapes, such as TiBaCaCuO (TBCCO-1223) and YBaCuO (YBCO-123) have been made by various surface coating or surface deposition techniques. Ideally an HTS wire should have a current density beyond $j_c \sim 10^5\ Acm^{-2}$ at operation temperatures from 65 K, but preferably above 77 K. The filling factor of HTS in the matrix needs to be high so that the engineering current density $j_e \geq 10^4\ Acm^{-2}$. j_c should not drastically decrease with applied field within the Tesla range. The helically wound HTS tape is cooled to below the critical temperature T_c of the HTS by a cooling fluid, preferably liquid nitrogen, passing through the inner support tube.

A cryostat layer may be arranged around the helically wound HTS tape to thermally insulate the cooled HTS tape from the electrically insulating material. Alternatively, however, the cryostat may be dispensed with. In this latter case, the electrically insulating material may be applied directly over the superconducting means. Alternatively a space may be provided between the superconducting means and the surrounding insulating material, the space either being a void space or a space filled with compressible material, such as a highly compressible foamed material. The space reduces expansion/contraction forces on the insulation system during heating from/cooling to cryogenic temperatures. If the space is filled with compressible material, the latter can be made semiconducting to ensure electrical contact between the semiconducting inner layer and the superconducting means.

Other designs of superconducting means are possible, the invention being directed to transformer windings, formed from superconducting cables of any suitable design having a surrounding electrical insulation of the type described above. For example other types of superconducting means may comprise, in addition to internally cooled HTS material, externally cooled HTS material or externally and internally cooled HTS material. In the latter type of HTS cable, two concentric HTS conductors separated by cryogenic insulation and cooled by liquid nitrogen are used to transmit electricity. The outer conductor acts as the return path and both HTS conductors may be formed of one or many layers of HTS tape for carrying the required current. The inner conductor may comprise HTS tape wound on a tubular support through which liquid nitrogen is passed. The outer conductor is cooled externally by liquid nitrogen and the whole assembly may be surrounded by a thermally insulating cryostat.

According to another aspect of the present invention there is provided an electric power transmission system characterised in that an SMES device according to said one aspect is connected to a high voltage source, preferably a high voltage dc source.

The SMES device may be in the form of a cable and preferably a cable with high inductance. The electrical insulation of the cable can be made of conductor tape or wire with several layers where all layers are wound in the same direction, instead of as conventionally winding the layers in opposite direction in order to compensate for the inductance. Such cable with an extruded insulation system could be directly incorporated into a transmission line, for example as one line of a bipolar dc system.

It is also possible to use such cable to build up a solenoid with high inductance.

The invention as herein described can also be used with conventional low-temperature superconducting materials and with coolants such as liquid helium.

It is also possible to use the invention wit an ac source. The losses are larger for an ac SMES device but if the losses are acceptable for the system to be designed, the principle of the invention is applicable.

Brief Description of the Drawings

Embodiments of the invention will now be described, by way of example only, with particular reference to the accompanying drawings, in which:

Figure 1 is a circuit diagram of an SMES device according to the present invention;

Figure 2 is a schematic sectional view, on an enlarged scale, through part of one embodiment of a high-temperature superconducting cable from which the coil of the SMES device of Figure 1 is wound;

Figure 3 is a schematic sectional view, on an enlarged scale, of another embodiment of high-temperature superconducting cable from which the coil of the SMES device of Figure 1 can be wound;

Figure 4 is a schematic view of two high voltage ac networks coupled together via a high voltage dc network and incorporating an SMES device on the dc side;

Figure 5 is a schematic view of an SMES incorporated in a high voltage dc network; and

Figure 6 is a schematic view of two converter stations with voltage source converters and combined with a high voltage bipolar dc link.

Figure 1 shows a coil 1 having an inductance L formed of high-temperature (T_c) superconducting (HTS) cable 12 (see Figure 2) which is connected with a high dc voltage source 2, e.g. the dc side of a high voltage ac-dc converter connected to an ac power transmission line. A switch 3 is connected in parallel with the high dc voltage source 2 and is operable to short-circuit the coil 1.

When the coil 1 is connected to the dc voltage source 2, a dc current I flows and charges the coil. Due to the high current density of the superconducting cable and its virtually zero resistance, energy is simply stored by closing the switch 3 and short-circuiting the coil. The energy in the coil is stored as magnetic energy having a value of $\frac{1}{2}.L.I^2$. The coil 1 is thus able to store electrical energy and to provide electrical power at a fast rate when required at times of peak consumption.

The superconducting cable 12 from which the coil 1 is formed comprises an inner tubular support 13, e.g. of copper or a highly resistive metal, such as copper-nickel alloy, on which is helically wound elongate HTS material, for example BSCCO tape or the like, to form a superconducting layer 14 around the tubular support 13. A cryostat 15, arranged outside the superconducting layer, comprises two spaced apart flexible corrugated metal tubes 16 and 17. The space between the tubes 16 and 17 is maintained under vacuum and contains thermal superinsulation 18. Liquid nitrogen, or other cooling fluid, is passed along the tubular support 13 to cool the surrounding superconducting layer 14 to below its critical superconducting temperature T_c. The tubular support 13, superconducting layer 14 and cryostat 15 together constitute superconducting means of the cable 12.

Solid electrical insulation, e.g. of plastics material, is arranged outside the superconducting means. The electrical insulation comprises an inner semiconducting layer 20, an outer semiconducting layer 21 and, sandwiched between these semiconducting layers, an insulating layer 22.

The layers 20-22 preferably comprise thermoplastics materials providing a substantially unitary construction. The layers may be in close mechanical contact with each other but are preferably solidly connected to each other at their interfaces. Conveniently these thermoplastics materials have similar coefficients of thermal expansion and are preferably extruded together around the inner superconducting means. The electrical insulation conveniently has an electric field stress of no more than 0.2 kV/mm.

By way of example only, the solid insulating layer 22 may comprise cross-linked polyethylene (XLPE). Alternatively, however, the solid insulating layer may comprise other cross-linked materials, low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polymethylpentene (PMP), ethylene (ethyl) acrylate copolymer, or rubber insulation, such as ethylene propylene rubber (EPR), ethylene-propylene-diene monomer (EPDM) or silicone rubber. The semiconducting material of the inner and outer layers 20 and 21 may comprise, for example, a base polymer of the same material as the solid insulating layer 22 and highly electrically conductive particles, e.g. particles of carbon black or metallic particles, embedded in the base polymer. The volume resistivity of these semiconducting layers, typically about 20 ohm·cm, may be adjusted as required by varying the type and proportion of carbon black added to the base polymer. The following gives an example of the way in which resistivity can be varied using different types and quantities of carbon black.

Base Polymer	Carbon Black Type	Carbon Black Quantity (%)	Volume Resistivity Ω·cm
Ethylene vinyl acetate copolymer/ nitrite rubber	EC carbon black	~15	350-400
-"-	P-carbon black	~37	70-10
-"-	Extra conducting carbon black, type I	~35	40-50
-"-	Extra conducting black, type II	~33	30-60
Butyl grafted polyethylene	-"-	~25	7-10
Ethylene butyl acrylate copolymer	Acetylene carbon black	~35	40-50
-"-	P carbon black	~38	5-10
Ethylene propene rubber	Extra conducting carbon black	~35	200-400

The outer semiconductive layer 21 is connected to a desired controlled electric potential, e.g. earth potential, at spaced apart regions along its length, the specific spacing apart of adjacent controlled potential or earthing points being dependent on the resistivity of the layer 21.

The semiconducting layer 21 acts as a static shield and by controlling the electric potential of the outer layer, e.g. to earth potential, it is ensured that the electric field of the superconducting cable is retained within the solid insulation between the semiconducting layers 20 and 21. Losses caused by induced voltages in the layer 21 are reduced by increasing the resistance of the layer 21. However, since the layer 21 must be at least of a certain minimum thickness, e.g. no less than 0.8 mm, the resistance can only be increased by selecting the material of the layer to have a relatively high resistivity. The resistivity cannot be increased too much, however, else the voltage of the layer 21 mid-way between two adjacent earthing points will be too high with the associated risk of corona discharges occurring.

Instead of, or in addition to, internally cryogenically cooling the HTS cable 12, the coil 1 and switch 3 may be enclosed within a cryostat 6 (shown schematically in dashed lines in Figure 1) for keeping the coil 1 at temperatures below the critical temperature of the superconducting means. In this case the thermally insulating cryostat 15 need not be included in the HTS cable described above with reference to Figure 2. Figure 3 shows a typical design of cable having no cryostat 15. In this case the electrical insulation, provided by the layers 20-22, is extruded directly over the superconducting layer 14 wound on the tubular support 13. Although not shown, an annular gap may be provided between the electric insulation and the layer 14 to cater for the differences in thermal expansion/contraction of the electrical insulation and the layer 14. This annular gap could be a void space or could be filled with compressible material, such as highly compressible foam material. If such an annular gap is provided, the semiconducting inner layer 20 is preferably placed in electrical contact with the superconducting layer 14. For example if the compressible foam material is included in the annular gap the foam material may be made semiconducting.

Figure 4 shows a high voltage system comprising two high voltage ac networks, N1 and N2, T1Y and T2Y are converter transformers in Y/Y coupling and T1D and T2D are converter transformers in Y/D coupling. SCR11, SCR12, SCR21 and SCR22 are series-connected 6-pulse line-commutated bridge-connected converters. The converters SCR11 and SCR12 are linked with the converters SCR21 and SCR22 via a dc link DCL which comprises an energy storage device in the form of a superconducting magnetic storage device SMES.

The voltage over the converters SCR11 and SCR12 is U1 and the voltage over converters SCR21 and SCR22 is U2. U1 and U2 are each controlled in a conventional manner by control equipment (not shown) connected with its respective

converter. The current I_d runs through the dc link DCL and the device SMES.

In the system shown in Figure 4, U1 - U2 = L*dI/dt, which means the charging and discharging of the device SMES can be controlled by the control angles of the converters. One or both converters can charge or discharge the SMES. By controlling U1=U2, the content of energy of the SMES can be unaffected.

Figure 5 shows the same basic high voltage system as Figure 4. In Figure 5, however, the superconducting magnetic energy storage device SMES is used as a storage device for the ac network N1 and is charged via the converters SCR11 and SCR12, with switch S1 closed and switch S2 open. During charging of the device SMES, the current through the coil can be measured and charging continues until a nominal value is reached. When the SMES is fully charged, S1 opens and S2 closes. For feeding the network N1, for example in the case of a power loss on the network, S1 closes and S2 is opened.

In the Figure 5 system, the superconducting magnetic energy storage device SMES is part of a high voltage dc transmission system with a dc link. A pole control device, PCM, is needed when providing the network N2 with power.

Figure 6 shows a high voltage system having two voltage-controlled converters VSC1 and VSC2, which are connected via a dc link in the form of a double cable TC. The dc link is bipolar in that the capacitors C11 and C12 and the capacitors C21 and C22 are respectively connected to ground at their connecting point. A superconducting magnetic energy storage device SMES is arranged at one pole of the converter VSC1. It is also possible to arrange the superconducting magnetic energy storage device in the form of a cable as one part of the bipolar dc link.

Although the invention has been described with specific reference to an SMES device having a coil for connection in series with a dc voltage source, the invention is also intended to embrace connection of the coil to an ac voltage source.

The term "high voltage" used in this specification is intended to mean up to 800 kV or even higher. An SMES device may be connected to such high voltage networks and at high powers of up to 1000 MVA. At high voltages, partial discharges, or PD, constitute a serious problem for known insulation systems. If cavities or pores are present in the insulation, internal corona discharges may arise whereby the insulating material is gradually degraded eventually leading to breakdown of the insulation. The electric load on the electrical insulation of the superconducting means of an SMES device according to the present invention is reduced by ensuring that the inner portion of the electrical insulation is at substantially the same electric potential as the superconducting means and that the outer portion of the electrical insulation is at a controlled potential. Thus the electric field is distributed substantially uniformly over the thickness of the electrically insulating portion of the insulation between the inner and outer potions. By having materials for the electrical insulation with similar thermal properties and with few defects in the layers or portions, the possibility of PD is reduced.

An additional advantage of the present invention is that, since the SMES device operates at high voltage, the current can be reduced for a given power density. Thus for a conventional SMES device operating at 20 kV, a similarly powered SMES device according to the invention can operate at about 150 kV resulting in a reduction of the current of about 7.5 times. Since the magnetic force in the cable is proportional to current x magnetic flux density (B), the magnetic force is effectively reduced about 7.5 times. Furthermore, the amount of semiconductor saved will, in this example, amount to approximately 7.5 times. Similarly, the

cooling losses will be essentially reduced. All these factors improve the economic attractiveness of the SMES device.

The present invention is not limited to high temperature superconductivity. Due to the high magnetic field in magnetic energy storage, low temperature superconductors are still attractive, even though they require cryostats operating between 1-15 K, depending on the type of low temperature superconductor utilised. Well known examples are based on Niobium, such as NbTi, Nb_3Sn and Nb_3Al. Other examples are V_3Ga and Nb_3Ge. The most common superconductor used is NbTi which can be utilised in magnetic field densities up to approximately 9 T at 4.2 K (or 11 T at 1.8 K). For higher field densities, NbTi cannot be used and is replaced by Nb_3Sn.